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PARAMETERIZATION OF THE SOLAR AND INFRARED RADIATIVE PROPERTIES--ETC(U)

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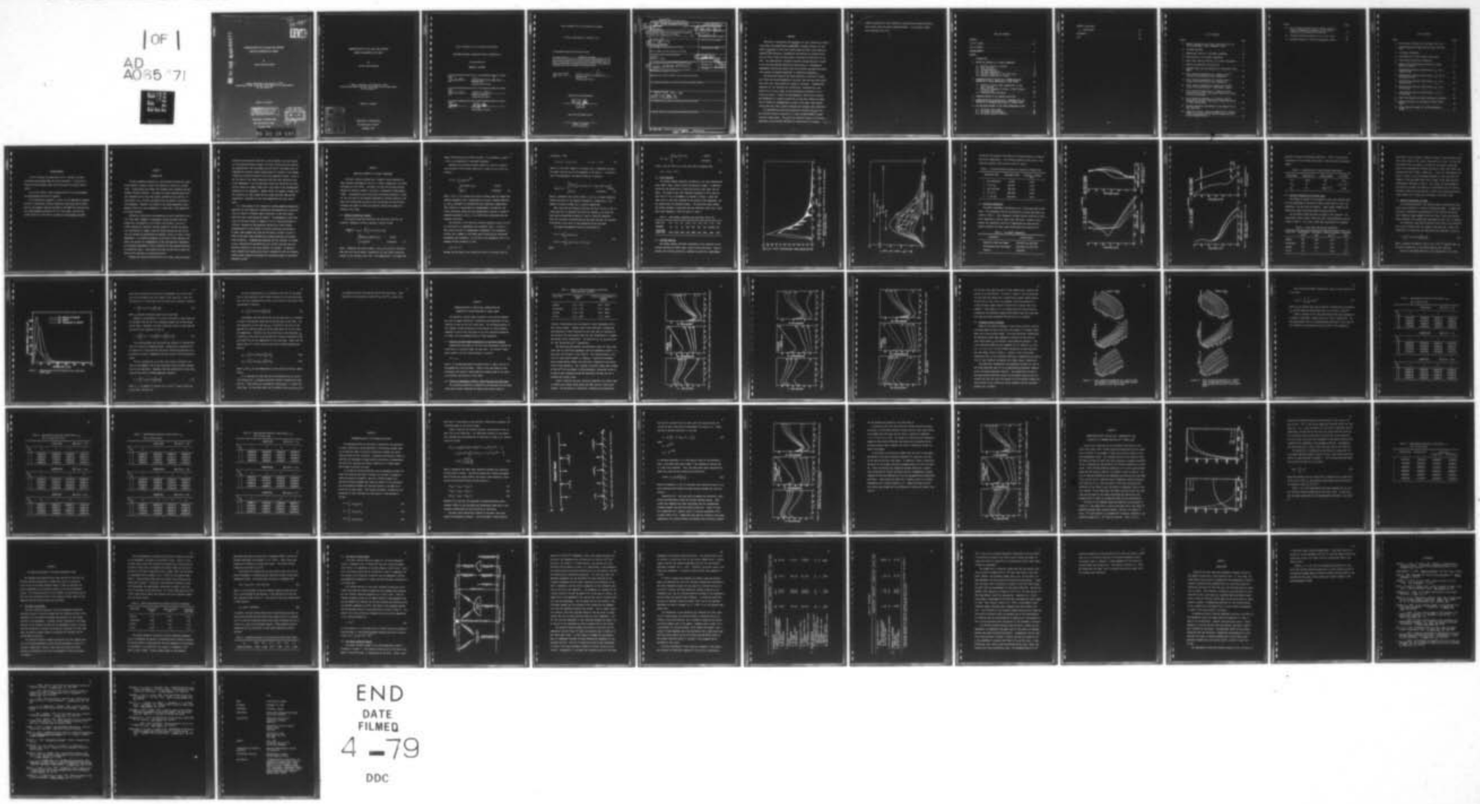

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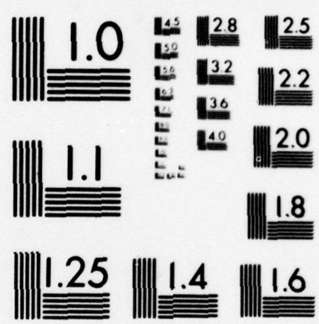
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PARAMETERIZATION OF THE SOLAR AND INFRARED RADIATIVE PROPERTIES OF CLOUDS

by

Gerard Donald Wittman

A thesis submitted to the faculty of The University of Utah in partial fulfillment of the requirements for the degree of

Master of Science

Department of Meteorology
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THE UNIVERSITY OF UTAH GRADUATE SCHOOL

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ABSTRACT

Reflection, transmission and absorption of solar radiation by ~~four~~ 4 cloud types (low ~~cloud~~, middle ~~cloud~~, and high clouds and stratus) are computed as functions of the solar zenith angle and cloud liquid water/ice content; and ~~The~~ the reflection, transmission and emission of infrared radiation by cirrus clouds are calculated as functions of ~~the~~ cloud ice content. The plane-parallel radiative transfer program employed is based on the discrete-ordinate method with applications to inhomogeneous atmospheres covering the entire solar and infrared spectrums and taking into account the gaseous absorption in scattering atmospheres.

The resulting values of the solar radiative properties of clouds are fitted with known mathematical functions involving the solar zenith angle and cloud liquid water/ice content as variables. Parameterized equations for the infrared flux reflectivity, transmissivity, and emissivity of cirrus clouds are ~~also~~ presented as functions of the cloud ice content. Effects of the atmospheric profile are discussed and the effects of surface reflectivity on the solar radiative properties of clouds are parameterized in terms of the water vapor absorptivity below the cloud, ground reflection and average cloud reflection.

The parameterized empirical-theoretical functions for the solar and infrared radiative properties of clouds are ~~utilized~~ used in a global radiation budget model. The resulting radiation balance of the earth-atmosphere system matched ~~the~~ satellite observations of planetary → (over)

(cont)

albedo, absorption of solar radiation, and upwelling infrared radiation more closely than did earlier computed models. The planetary albedo was calculated to be 0.31.

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ACKNOWLEDGMENTS

I wish to express my appreciation to Dr. Kuo-Nan Liou whose assistance and guidance made this thesis possible. I also wish to thank my fellow students whose advice and quick wit helped significantly.

To my wife, Carolyn, goes my appreciation for her encouragement and understanding during this research.

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CHAPTER 1

INTRODUCTION

The most important regulators of the radiation balance are clouds, which regularly occupy at least fifty percent of the sky on a global scale. Clouds absorb and scatter the incoming solar radiation and emit thermal infrared radiation. The amount of energy absorbed and/or emitted represents one of the prime sources determining the stability of cloud layers and is further associated with the general circulation of the atmosphere. Moreover, the albedo of the earth-atmosphere system depends crucially on such parameters as cloud cover, cloud composition and cloud structure.

Reflection, transmission and absorption of solar radiation by various cloud types imbedded in atmospheres containing water vapor was extensively investigated by Liou (1976), and recently, Liou et al. (1978) extended the radiative transfer program to include the absorption contribution of oxygen, ozone and carbon dioxide and the absorption and scattering contributions by aerosols typical of those in clear atmospheres. The radiation program, as utilized in this research, has taken into account the inhomogeneity of the plane-parallel atmosphere, the wavelength dependence of solar radiation and the gaseous absorption in scattering layers. Calculations have been carried out to cover the entire solar spectrum on a band-by-band basis.

Although the radiation characteristics of clouds, whose horizontal

extents are much greater than their vertical depths, can be evaluated to yield good accuracies by means of current existing transfer methods, the computational time requirement and the effort involvement make the comprehensive transfer program impracticable for studies of the weather, climate and radiation balance of the earth-atmosphere system. Owing to the intricacy of the cloud interaction with the solar radiation field of the atmosphere, a set of prescribed values for reflection and transmission values has normally been used in the study of the thermodynamic properties of the atmosphere. Manabe (1975), for example, assumed that the reflection of high, middle and low clouds were 20%, 48% and 89%, respectively, regardless of the cloud composition and solar zenith angle.

It is the purpose of this research to provide empirical-theoretical equations for the reflection, transmission and absorption of solar radiation by clouds of different type as functions of the solar zenith angle and cloud liquid water/ice content. The mathematical known functions are derived by means of numerical fits of the precalculated reflection, transmission and absorption values for a black surface. Parameterization of the effects of surface reflection and absorption by water vapor between the cloud and the earth's surface is given in terms of the water vapor absorptivity, ground reflection and average cloud reflection. Parameterized equations for the infrared flux reflectivity, transmissivity and emissivity of a cirrus cloud are also presented as functions of the cloud vertical ice content. In addition, these parameterized equations are used in conjunction with the radiative transfer model program to determine the radiation balance of the earth-atmosphere system.

CHAPTER 2

RADIATIVE TRANSFER IN A CLOUDY ATMOSPHERE

The basic radiation scheme used is based on the plane-parallel model recently developed by Liou et al. (1978), Freeman and Liou (1978), and Roewe and Liou (1978). The model utilizes the discrete-ordinate method for radiative transfer, originally introduced by Chandrasekhar (1950). The method has been found quite satisfactory because it allows for the solutions of the integral-differential transfer equation to be explicitly derived and can easily take into account the distribution, thickness and types of clouds and aerosols, making the scheme well suited to this study.

2.1 Method of Radiative Transfer

The transfer equations describing the radiation field for the azimuthal independent diffuse intensity I may be written

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\tilde{\omega}_o}{2}\int_{-1}^{+1} P(\mu,\mu')I(\mu,\mu')d\mu' - \begin{cases} \frac{\tilde{\omega}_o}{4} F_o P(\mu,\mu_o)\exp(-\tau/\mu_o) & \text{(solar)} \\ (1-\tilde{\omega}_o)B_\nu(T) & \text{(Infrared)} \end{cases} \quad (1)$$

where τ represents the optical depth, μ and μ_o the cosine of the emergent and solar zenith angles, respectively, $\tilde{\omega}_o$ the single scattering albedo, F_o the incident solar flux, T the temperature, P the normalized

phase function and B_ν the Planck function. All parameters, except T, μ and μ_o are wavelength or wavenumber dependent.

Employing the discrete-ordinate method for radiative transfer, the solutions of the transfer equations as shown by Liou (1973) are given by

$$I(\tau,\mu_i) = \sum_j L_j\phi_j(\mu_i)e^{-k_j\tau} + \begin{cases} Z(\mu_i)\exp(-\tau/\mu_o) & \text{(solar)} \\ B_\nu(T) & \text{(Infrared)} \end{cases} \tag{2}$$

where i and j (-n,n) denote the discrete streams (positive upward and negative downward) used in approximating the basic transfer equation, ϕ_j and k_j represent the eigenfunction and eigenvalue, respectively, the Z-function is associated with Chandrasekhar's H-function, the single scattering albedo and the expanded phase function in terms of Legendre polynomials, and L_j's are coefficients determined from the boundary conditions.

The solutions of the radiative transfer equations given by Eq. (2) are applicable to a homogeneous and isothermal layer. In order to apply such solutions to inhomogeneous atmospheres, the atmosphere is divided into a number of sub-layers each of which may be considered homogeneous and isothermal. At the top of the atmosphere there is no downward diffuse intensity so that

$$I_1(o,-\mu_i) = 0. \tag{3}$$

Between the sub-layers, the intensities from all directions must be

continuous. Thus,

$$I_\ell(\tau_\ell,\mu_i) = I_{\ell+1}(\tau_\ell,\mu_i), \qquad \ell = 1,2,\ldots, N-1 \tag{4}$$

where N is the total number of sub-layers and τ_ℓ represents the optical depth from the top of the atmosphere to the layer ℓ. At the bottom of the atmosphere, the upward intensity is given by

$$I_N(\tau_N,+\mu_i) = \begin{cases} \dfrac{A_s}{\pi}\left[2\pi \displaystyle\sum_{i=1}^{n} a_i\mu_i I(\tau_N,-\mu_i) + \pi\mu_o F_o \exp(-\tau_N/\mu_o)\right] & \text{(solar)} \\ B_\nu(T_s) & \text{(Infrared)} \end{cases} \tag{5}$$

where A_s represents the surface albedo, a_i and μ_i are Gauss weighting factors and zeros of the Legendre polynomials, respectively, n the number of discrete streams and T_s surface temperature.

Upon inserting the intensity solution into Eqs. (3)-(5), a set of linear equations is obtained from which the unknown L_j for each sub-layer may be determined by means of a matrix inversion technique. After the constants of proportionality have been derived, the intensity distribution at any level in the atmosphere may be evaluated.

The upward and downward fluxes are then given by

$$\begin{aligned} F^{\uparrow}(\tau) &= 2\pi \sum_{i=1}^{n} a_i\mu_i I(\tau,\mu_i) \\ F^{\downarrow}(\tau) &= -2\pi \sum_{i=1}^{n} a_i\mu_i I(\tau,-\mu_i) - S(\tau,-\mu_o) \end{aligned} \tag{6}$$

where

$$S(\tau,-\mu_o) = \begin{cases} \pi\mu_o F_o \exp(-\tau/\mu_o) & \text{(Solar)} \\ 0 & \text{(Infrared)} \end{cases} \tag{7}$$

Finally, the net flux for a given layer may be computed from

$$F(\tau) = F^{\uparrow}(\tau) + F^{\downarrow}(\tau) \ . \tag{8}$$

2.2 Solar Spectrum

The primary gaseous absorbers considered in the solar spectrum are water vapor, ozone, carbon dioxide and molecular oxygen. In addition, scattering and absorption by clouds and aerosols were taken into account. The range of the solar spectrum considered in this study was that from 0.2 to 3.4 micrometers as plotted in Figure 1, where the inner curve is the solar spectrum at the bottom of the atmosphere, and the shaded areas are absorption bands. The particular bands chosen, the primary absorber in each band and the fractional solar flux in each band (from Thekaekara, 1974) are given in Table 1.

Table 1. Solar Bands, Absorbers and Fractional Solar Flux

BAND (μm)	0.3	0.5	0.7	0.94	1.10	1.38	1.87	2.70	3.20
ABSORBER	O_3	O_3	O_2	H_2O	H_2O	H_2O	H_2O	CO_2/H_2O	H_2O
FRACTIONAL SOLAR FLUX	.0872	.2696	.2034	.1347	.0892	.1021	.0622	.0300	.0216

2.3 Infrared Spectrum

The primary gaseous absorbers considered by this research in the infrared spectrum are water vapor, carbon dioxide and ozone. Figure 2 displays the infrared spectrum as obtained by satellite, superimposed

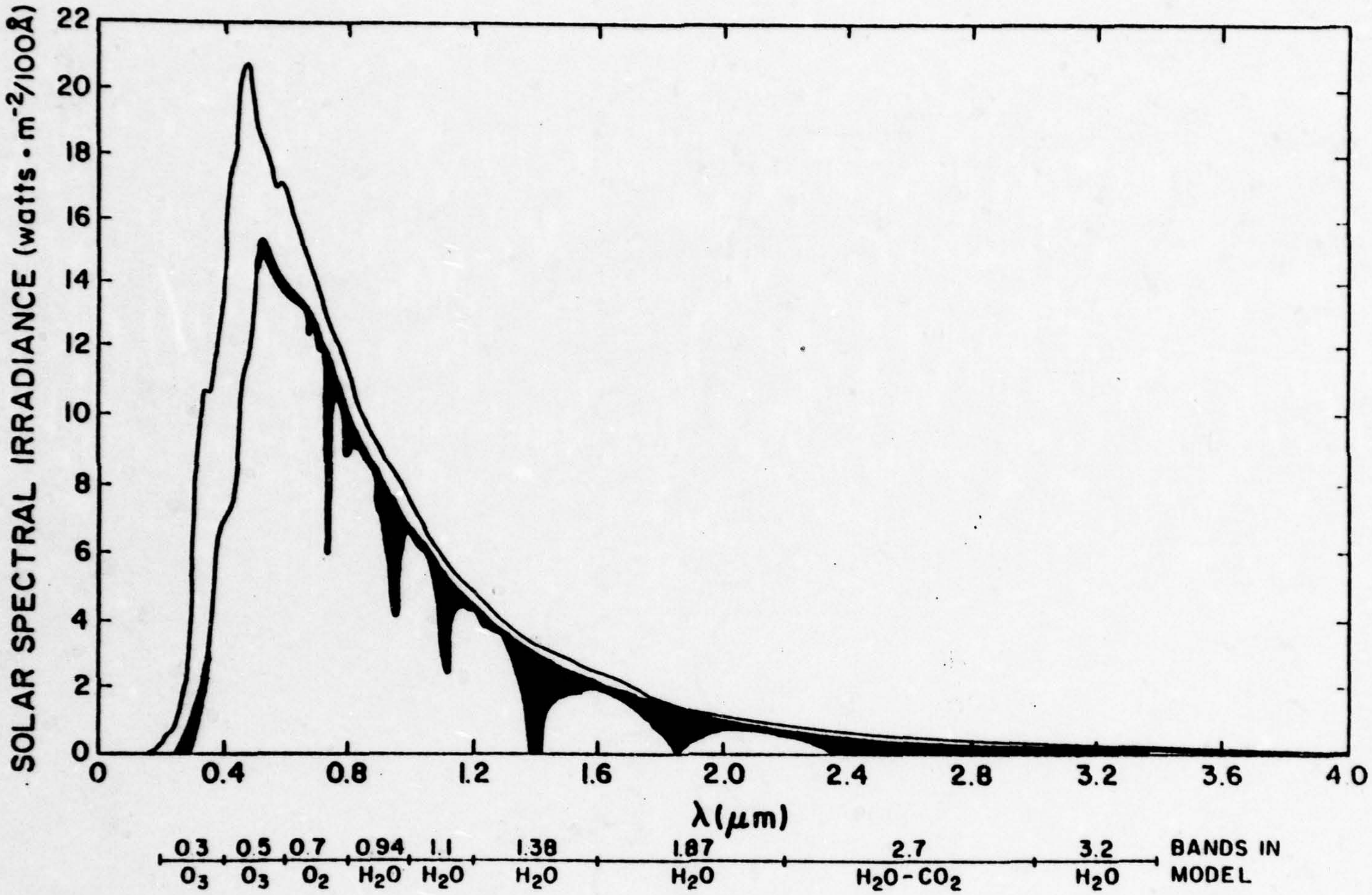

Figure 1. Spectral energy curve of solar radiation at the top of the atmosphere, after Thekaekara (1974).

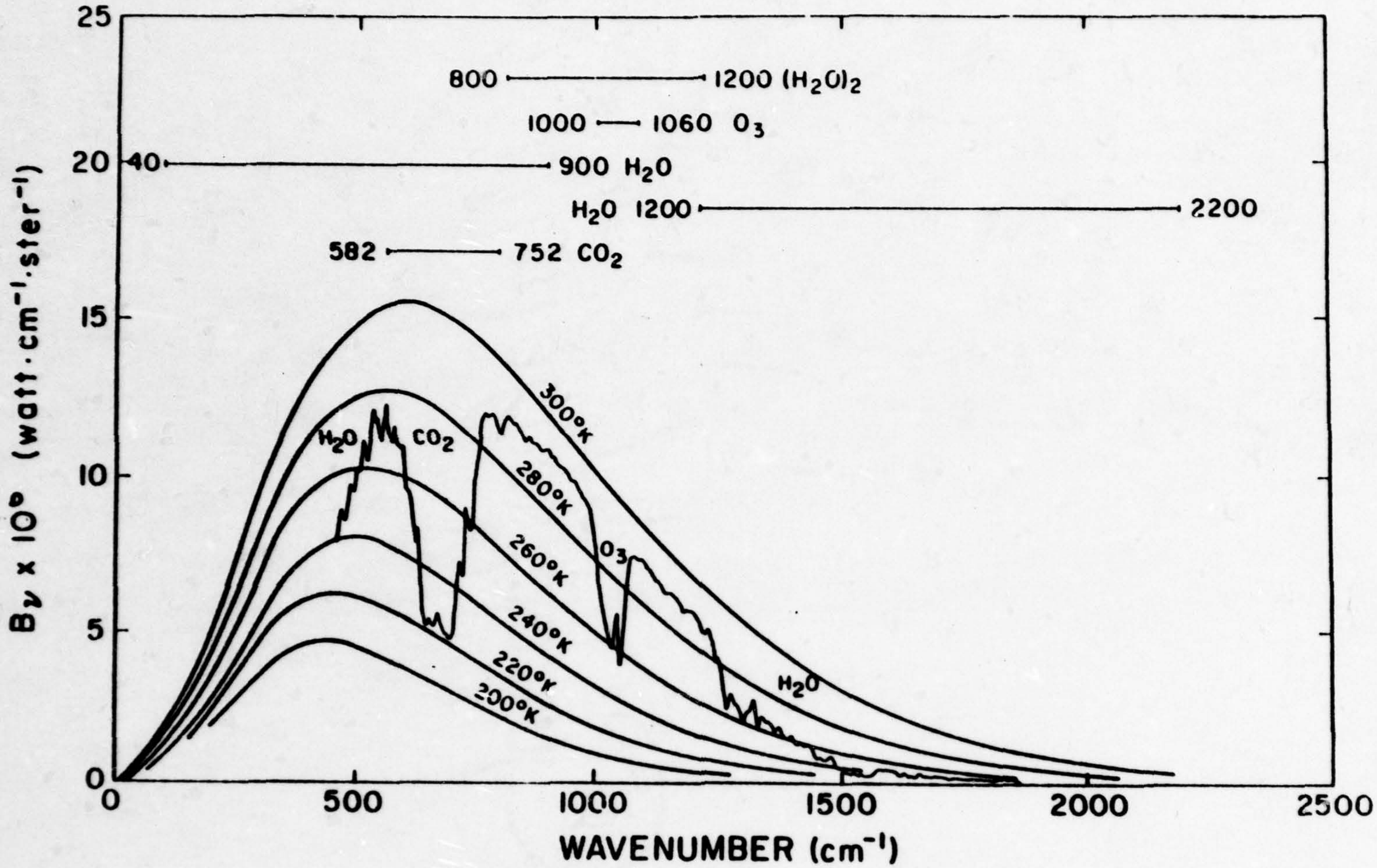

Figure 2. Infrared spectrum.

on plots of the spectral distribution of thermal emission for several earth-like temperatures. The infrared absorption bands used in this study are labeled on the plot and listed in Table 2.

Table 2. Infrared Absorption Bands and Fractional Infrared Flux

Absorption Band	Wavenumber Range	Fractional Infrared Flux
1. H_2O rotational	40-900	0.615
2. 15 μm CO_2	582-752	0.150
3. H_2O continuum	800-1200	0.160
4. 9.6 μm O_3	1000-1065	0.024
5. 6.3 μm H_2O	1200-2200	0.051

2.4 The Model Atmospheres

Five model atmospheres (McClatchey et al., 1971) were used in this study. The atmospheres and the latitude belts to which they apply are listed in Table 3. Each atmosphere includes vertical profiles of pressure, temperature, density, water vapor and ozone. Figures 3 and 4 present the atmospheric profiles of temperature and ozone density. Figure 5 displays the water vapor distributions and Figure 6 the

Table 3. Five Model Atmospheres

Atmosphere	Latitude Belts
Subarctic Winter and Summer	90^oN-60^oN and 90^oS-60^oS
Midlatitude Winter and Summer	60^oN-30^oN and 60^oS-30^oS
Tropical	30^oN-30^oS

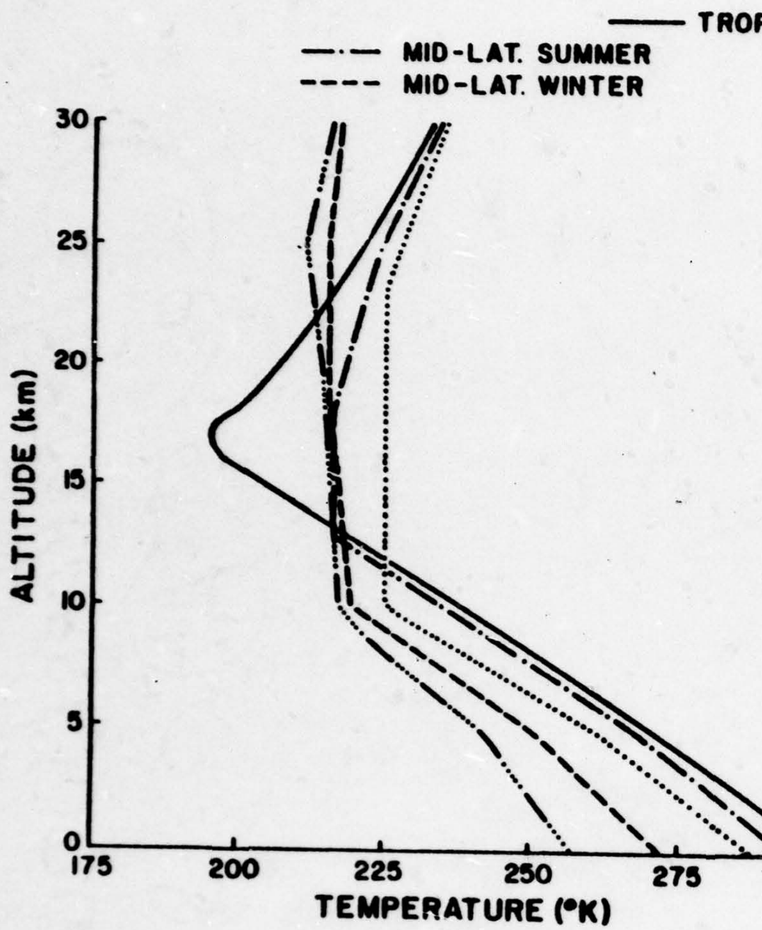

Figure 3. Temperature profiles in the model atmospheres.

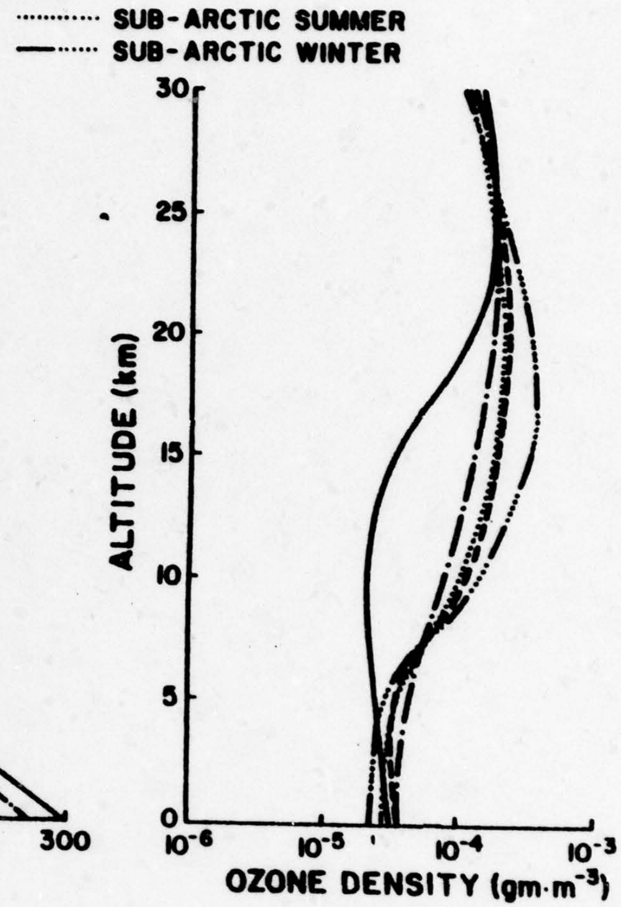

Figure 4. Ozone profiles in the model atmospheres.

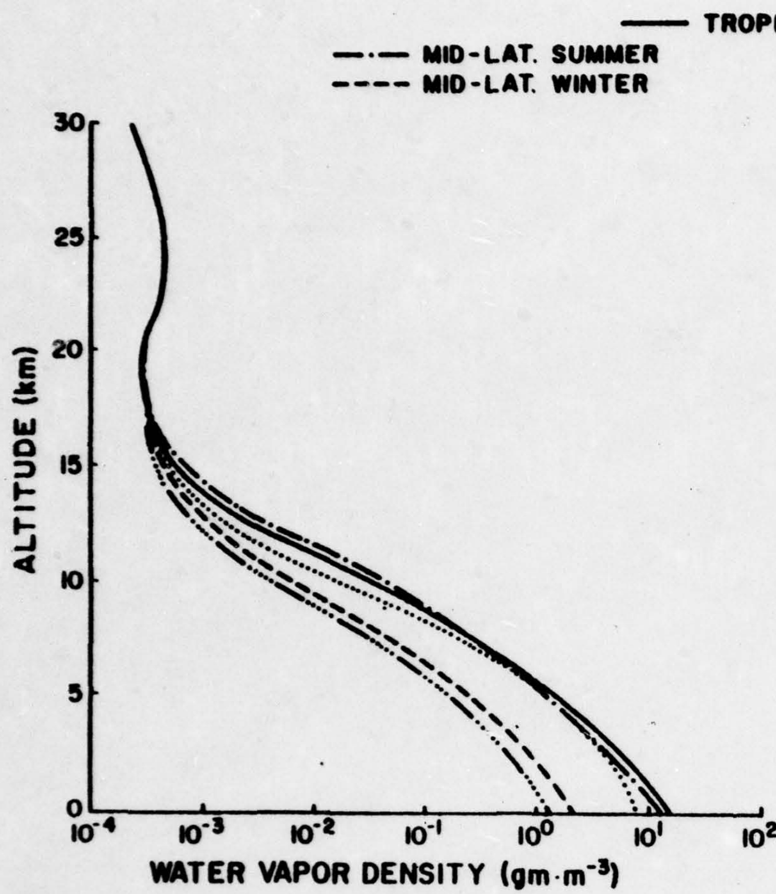

Figure 5. Water vapor density profiles in the model atmospheres.

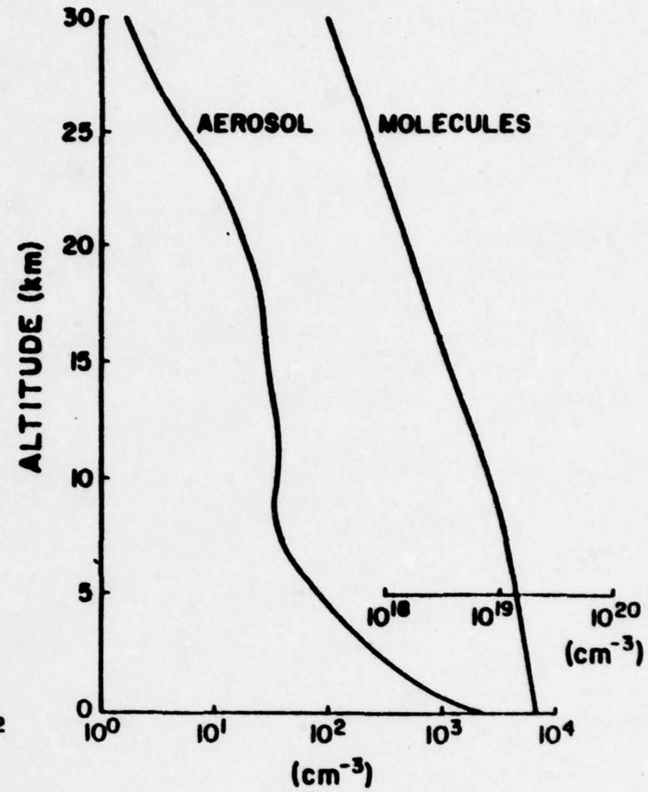

Figure 6. Aerosol and molecular distributions.

profiles of aerosol and molecular densities. Table 4 lists the concentrations of the uniformly mixed gases, carbon dioxide and molecular oxygen.

Table 4. Concentrations of the Uniformly Mixed Gases

Constituent	Molecular Wt.	ppm by Volume	g cm^{-2}/mb
Air	28.97	10^6	1.02
CO_2	44	330	5.11×10^{-4}
O_2	32	2.095×10^5	0.236

2.5 Physical Properties of the Cloud Types

The effects of clouds on the transfer of solar and infrared radiation are determined by the particle phase (liquid water or ice), concentration, size and size distribution. These factors combine to determine the single scattering albedo and phase function.

Four different cloud types were utilized in this research. The cloud height values (London, 1957) and other cloud parameters used are listed in Table 5. The cirrus clouds were considered to be composed

Table 5. Cloud Types and Physical Properties

Cloud Type	Concentration (cm^{-3})	Drop Radius (μm)	Water/Ice Content (g m^{-3})	Cloud Base (km)
Cumulus	300	0-40	0.33	1.8
Altostratus	450	0-13	0.24	4.1
Stratus	178	0-40	0.78	1.4
Cirrus	0.1	----	0.05	10.2

exclusively of ice cylinders, randomly oriented in the horizontal plane, with a mean length of 200 μm and a mean radius of 30 μm. The drop-size distributions for the cumulus, altostratus and stratus clouds were based on the observations of Battan and Reitan (1957), Diem (1948) and Singleton and Smith (1960), respectively. These size distributions are shown in Figure 7, the curves being presented in such a way that the integral of the area under each curve is equal to the total particle concentration indicated in Table 5. All clouds, for the purposes of the radiative transfer calculations, are considered to be of infinite horizontal extent and plane parallel. Within the infrared spectrum all clouds except cirrus clouds were considered to be black bodies.

2.6 Radiative Properties of Clouds

As described previously, the radiation model calculates the transfer of solar radiation in a series of absorption bands. To obtain the reflection, transmission and absorption of the cloud for the entire solar spectrum, proper summation over the fluxes in each sub-spectral region weighted by the appropriate percentage of solar flux is required.

The reflection r may then be defined as the ratio of the reflected flux to the incident solar flux normal to the cloud top. Hence, the reflection of a cloud layer for the entire solar spectrum is given by

$$r = \sum_i \left[F_i^{\uparrow}(\tau_t)/F_i^{\downarrow}(\tau_t)\right]\left[f_i/S_o\right], \tag{9}$$

where f_i denotes the amount of solar flux in the i^{th} spectral band, S_o the solar constant and τ_t the optical depth at the cloud top.

Similar to the above definition, the transmission t of a cloud

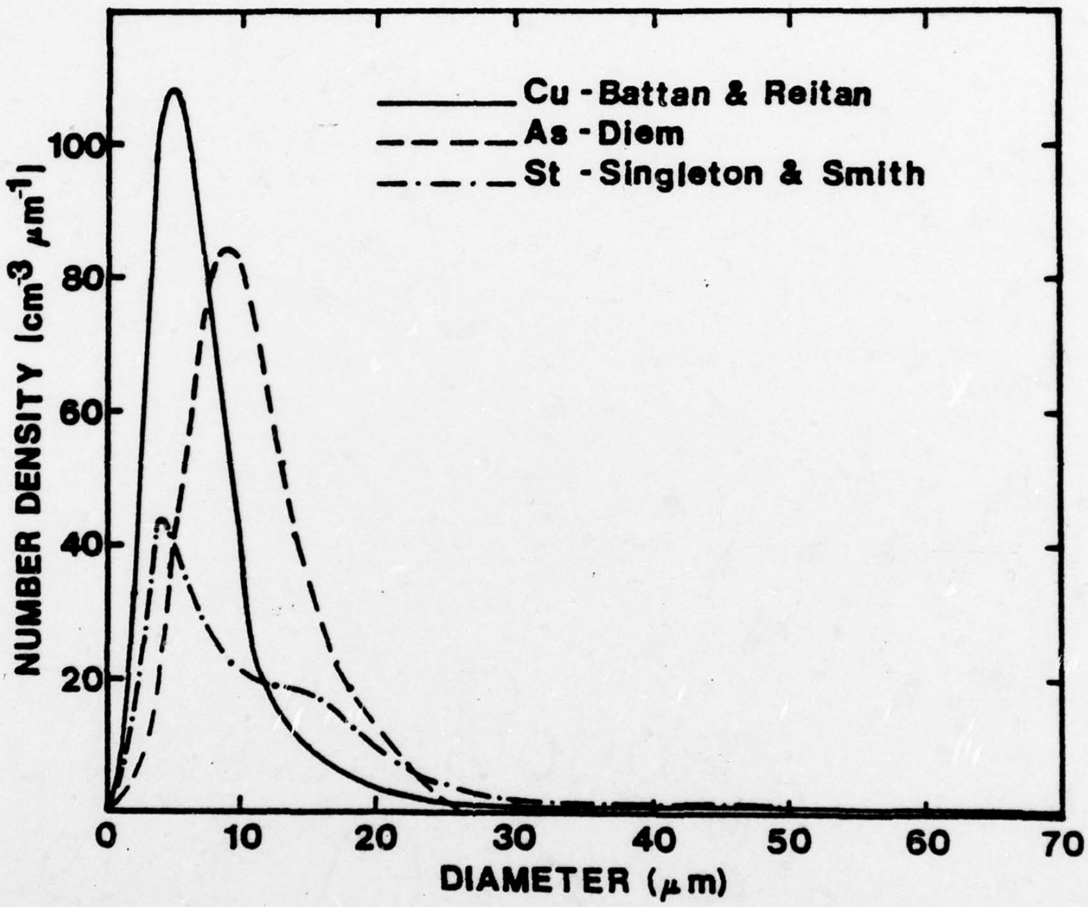

Figure 7. Observed drop-size distributions for three major cloud types.

layer may be defined as the ratio of the downward flux at the cloud base to the incident solar flux normal to the cloud top. Thus, the transmission of a cloud layer for the entire solar spectrum is given by

$$t = \sum_i \left[F_i^{\downarrow}(\tau_b)/F_i^{\downarrow}(\tau_t)\right]\left[f_i/S_o\right] , \tag{10}$$

where τ_b denotes the optical depth at the cloud base.

Moreover, the absorption α of solar flux within a cloud layer can be evaluated from the net flux divergence between the top and bottom of the cloud. Therefore, the total absorption within a cloud layer for the entire solar spectrum is given by

$$\alpha = \sum_i \left\{\left[F_i(\tau_t) - F_i(\tau_b)\right]/\left[F_i^{\downarrow}(\tau_t)\right]\right\}\left\{f_i/S_o\right\} \tag{11}$$

The radiation model also calculates the transfer of infrared radiation in a series of absorption bands. Reflectivity, transmissivity and emissivity of the cloud for the entire infrared spectrum may also be defined in terms of summations over the fluxes in each sub-spectral region.

The flux reflectivity r_F of the cirrus cloud is defined as the ratio of the downward flux at the cloud base to the incident infrared flux at the cloud base. Therefore, the flux reflectivity of the cirrus cloud for the entire infrared spectrum is given by

$$r_F = \sum_i \left[F_i^{\downarrow}(\tau_b)/F_i^{\uparrow}(\tau_b)\right]\left[f_i/R_o\right] \tag{12}$$

where f_i is the amount of infrared flux in the i^{th} spectral band and R_o the total infrared flux.

The flux transmissivity t_F is defined as the ratio of the upward flux at the cloud top to the incident infrared flux at the cloud base. Thus, the flux transmissivity of the cirrus cloud for the entire infrared spectrum is given by

$$t_F = \sum_i \left[F_i^{\uparrow}(\tau_t)/F_i^{\uparrow}(\tau_b)\right]\left[f_i/R_o\right] \tag{13}$$

Furthermore, the flux emissivity of the cloud layer ε_F is defined in terms of the emission from the top and the base of the cloud. The flux emissivity at the cloud top ε_{Ft} is defined as the ratio of the emitted flux from the cloud top to the black body flux for the cloud top temperature. Similarly the flux emissivity at the cloud base ε_{Fb} is defined as the ratio of the emitted flux from the cloud base to the black body flux for the temperature of the cloud base. Hence, the flux emissivities of a cirrus cloud for the entire infrared spectrum are given by

$$\varepsilon_{Ft} = \sum_i \left[F_i^{\uparrow}(\tau_t)/\pi B_{\bar{\nu}_i}(T_t)\right]\left[f_i/R_o\right] \tag{14a}$$

$$\varepsilon_{Fb} = \sum_i \left[F_i^{\downarrow}(\tau_b)/\pi B_{\bar{\nu}_i}(T_b)\right]\left[f_i/R_o\right] \tag{14b}$$

where T_t and T_b are the temperatures at the cloud top and base, respectively.

It is important to note that the flux transmissivity t_F and the flux reflectivity r_F represent quantities without including the cloud emission. These values are evaluated by letting $B_{\bar{\nu}}(T) = 0$ within the cloud layer. On the other hand, the flux emissivities ε_{Ft} and ε_{Fb} are

calculated using only the emission due to the cloud layer. These quantities are evaluated by letting $F^{\uparrow}(\tau_b)$ and $F^{\downarrow}(\tau_t)$ equal zero.

CHAPTER 3

PARAMETERIZATION OF REFLECTION, TRANSMISSION AND ABSORPTION OF SOLAR RADIATION BY CLOUD LAYERS

The radiative transfer model discussed in the previous chapter was used to compute reflection, transmission and absorption of solar radiation by each of the four cloud types. The following sections of this chapter include discussions of the effects of cloud thickness, atmospheric profile and cloud type on the solar radiative properties of clouds, and the parameterization of these properties.

3.1 Radiative Transfer Model Computations in the Solar Spectrum

Computations were made for various cloud thicknesses, holding the cloud base at a constant height for each case. The vertical liquid water content W of each cloud thickness is given by

$$W = w \, \Delta z, \tag{15}$$

where w is the measured water/ice content given in Table 5 and Δz is the geometrical cloud thickness. Table 6 lists the range of cloud thicknesses and vertical liquid water/ice contents used in the radiative transfer calculations of this study.

3.2 Effects of Atmospheric Profile, Cloud Thickness and Cloud Type

The resulting reflection, transmission and absorption by the cloud layer were initially obtained for cumulus and stratus clouds in

Table 6. Range of Cloud Thicknesses and Vertical Liquid Water/Ice Contents

Cloud Type	Thickness (km)	Vertical Liquid Water/Ice Content ($g \cdot m^{-2}$)
Cumulus	0.15 - 2.25	49.5 - 742.5
Altostratus	0.10 - 1.50	24.0 - 360.0
Stratus	0.50 - 0.75	39.0 - 585.0
Cirrus	0.10 - 2.90	5.2 - 150.4

tropical, midlatitude winter and subarctic winter atmospheres with a zero surface albedo. Figures 8 and 9 show reflection, transmission and absorption of solar radiation by the cloud layer as functions of the cosine of the solar zenith angle for four thicknesses of a cumulus and stratus cloud, respectively. The values of W_1, W_2, W_3 and W_4 are 50, 150, 250 and 450 $g \cdot m^{-2}$, respectively.

The reflection, transmission and absorption values for both cloud types show no significant dependence upon the atmospheric profile. In each case, the variance is less than 2%. The cloud thickness or the vertical liquid water content is, however, a significant parameter whose change greatly affects the reflection, transmission and absorption of solar radiation. For a change in vertical liquid water content of 400 $g \cdot m^{-2}$ (0.5 km change in cloud thickness), reflection varies by as much as 43%, transmission 56% and absorption 12% when the sun is overhead the stratus cloud.

Figure 10 depicts the solar radiative properties for several cases of cumulus and stratus clouds having the same vertical liquid water content. The variations in reflection, transmission and absorption

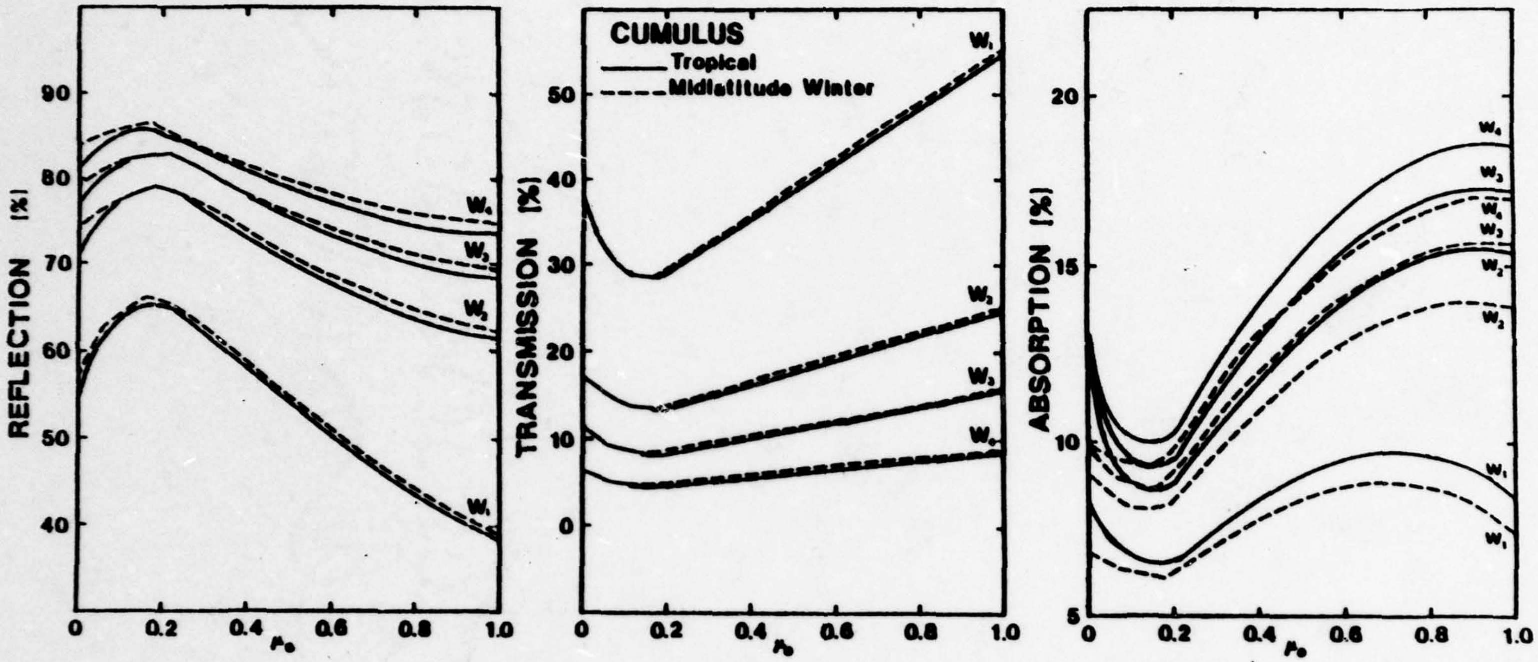

Figure 8. Solar radiative properties of a cumulus cloud in tropical and midlatitude winter atmospheres.

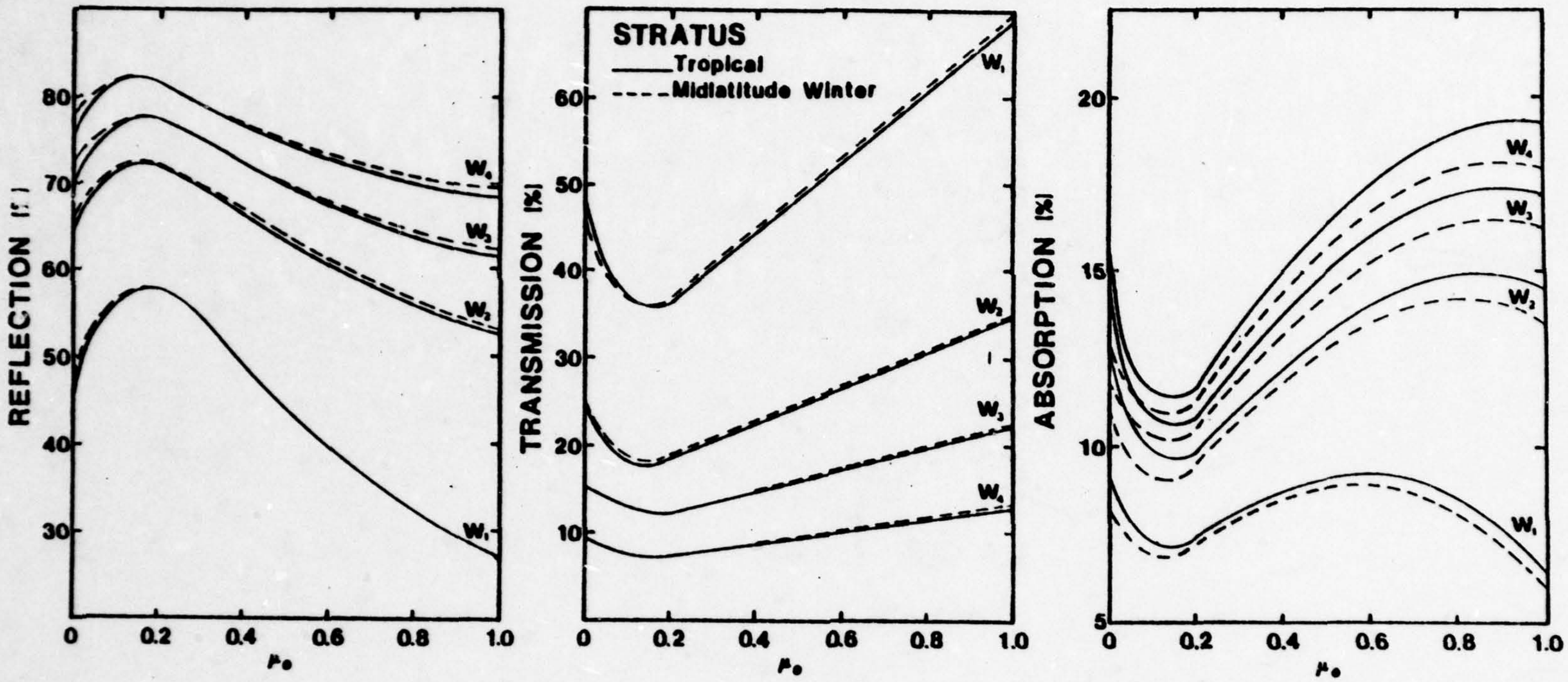

Figure 9. Solar radiative properties of a stratus cloud in tropical and midlatitude winter atmospheres.

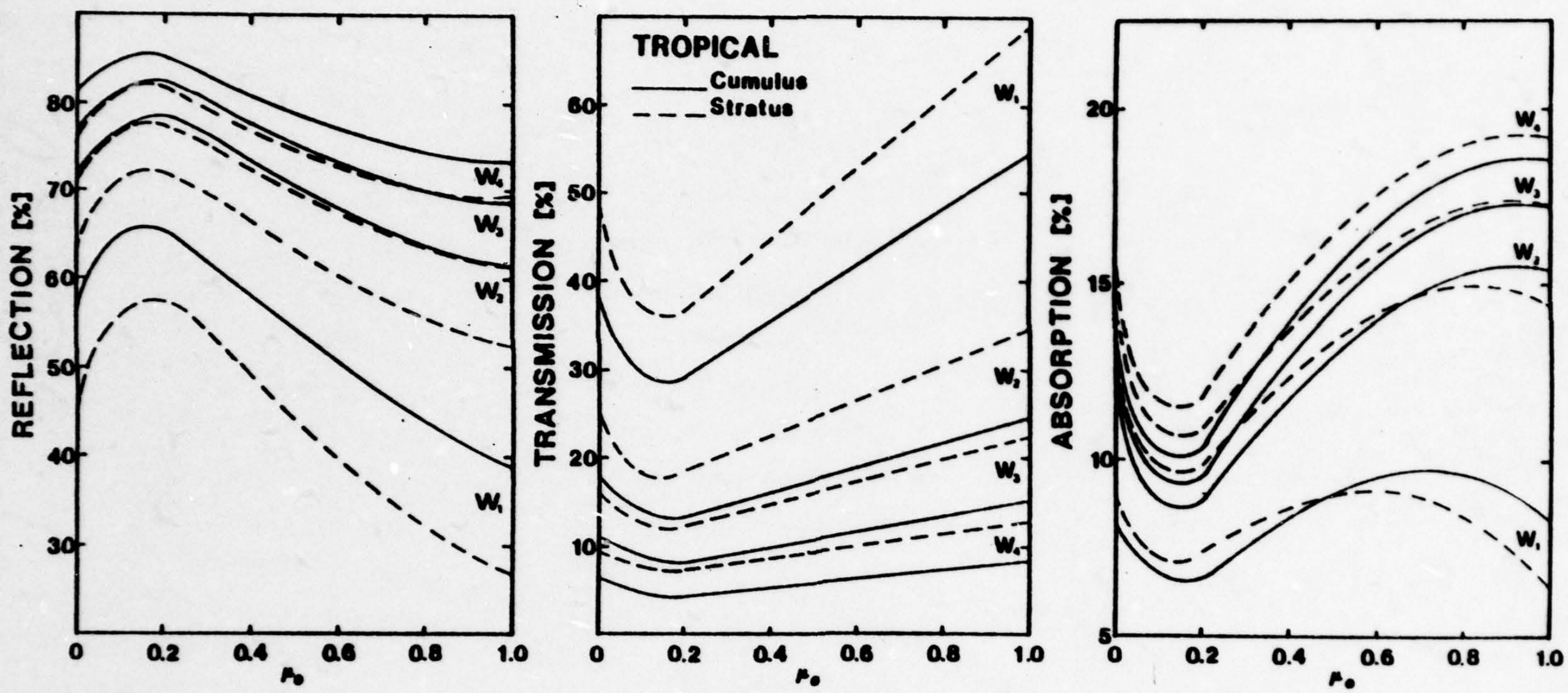

Figure 10. Solar radiative properties of cumulus and stratus clouds of the same vertical liquid water content.

for the two cloud types are due to cloud compositions, primarily the particle size distribution. As shown in Figure 7, the distributions are such that the cumulus has a significantly greater number density of particles of less than 12 μm diameter, while the stratus has a slightly greater number density of particles of greater than 12 μm diameter. From Figure 10, it is evident that the cloud reflection, transmission and absorption depend significantly upon the cloud type, with some variations exceeding 15% when the sun is overhead.

3.3 Parameterization Procedures

Based on the results presented in the previous section, calculations were made for each of the four cloud types in a tropical atmosphere with a zero surface albedo. The cloud reflection, transmission and absorption values were computed as functions of the cosine of solar zenith angle μ_o and vertical liquid water/ice content W. The solar radiative properties were computed for six values of μ_o (0.01, 0.2, 0.4, 0.6, 0.8, 1.0) and fifteen thicknesses of each cloud type over the ranges listed in Table 6. Figures 11 and 12 are three-dimensional plots of the resulting reflection, transmission and absorption of solar radiation by cumulus and stratus clouds, respectively.

The reflection, transmission and absorption surfaces for each of the cloud types were then fit to an approximating polynomial equation using a bivariate regression analysis. The coefficients of each of the approximating predictors within the polynomial equation were calculated such that the sum of the square of the differences between the actual values of the surface and values computed from the polynomial equation was a minimum.

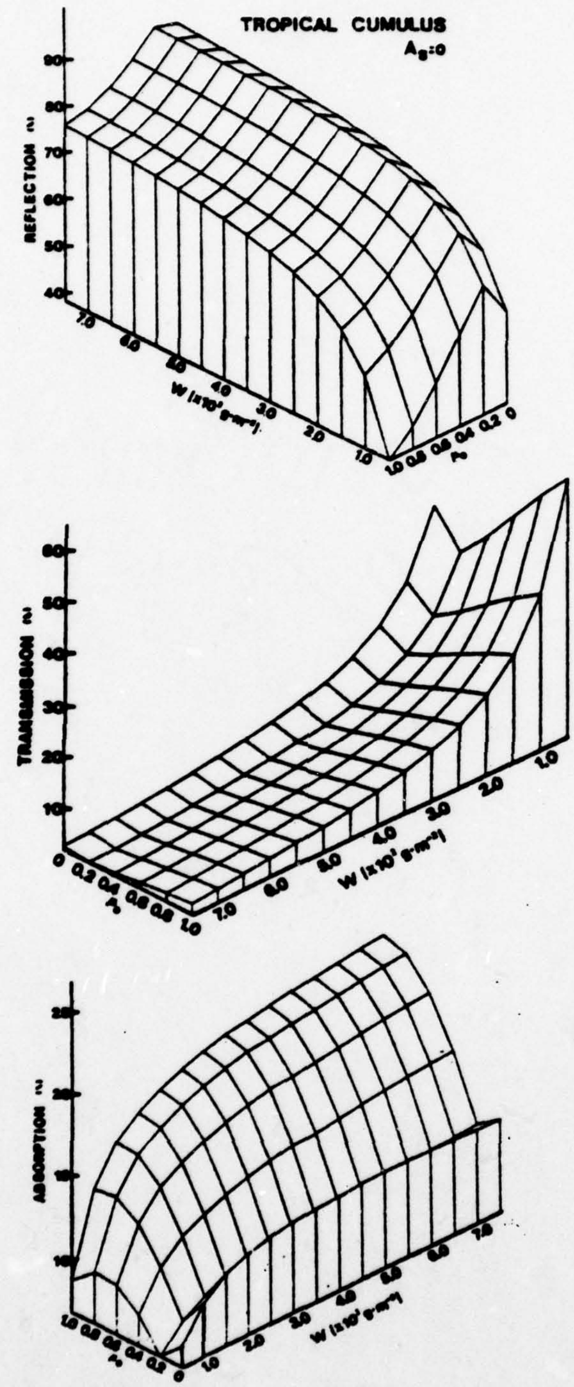

Figure 11. Solar radiative properties of a cumulus cloud as functions of vertical liquid water content and cosine of solar zenith angle.

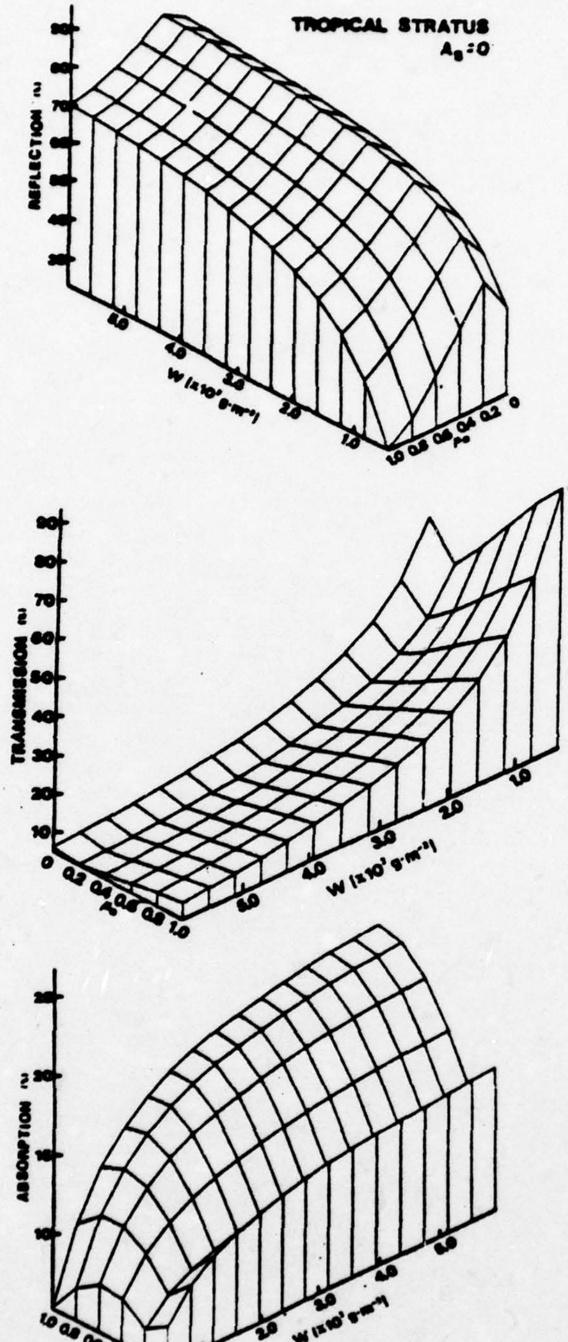

Figure 12. Solar radiative properties of a stratus cloud as functions of vertical liquid water content and cosine of solar zenith angle.

The following polynomial equation was found to yield the best fit of the data:

$$S(\mu_o, W) = \sum_{i=0}^{3} \sum_{j=0}^{3} b_{ij} \mu_o^{\,i} W^j \tag{16}$$

where $S(\mu_o, W)$ denotes the cloud reflection, transmission or absorption, b_{ij} are the predictor coefficients and W is in units of $10^2 g \cdot m^{-2}$.

Tables 7 through 10 list the coefficients which were computed for a cumulus, altostratus, stratus and cirrus cloud, respectively. The root mean square error of the approximating functions is less than 2% for reflection and transmission and less than 1% for absorption.

Table 7. Approximating predictor coefficients, b_{ij}, for a cumulus cloud

REFLECTION RMS Error = 1.5%

i \ j	0	1	2	3
0	.51771E+00	.18270E+00	-.35851E-01	.23478E-02
1	.72387E+00	-.27109E+00	.51303E-01	-.34428E-02
2	-.21499E+01	.75225E+00	-.14588E+00	.97306E-02
3	.12157E+01	-.40120E+00	.78145E-01	-.52224E-02

TRANSMISSION RMS Error = 1.7%

i \ j	0	1	2	3
0	.43642E+00	-.22727E+00	.44702E-01	-.29117E-02
1	-.66319E+00	.35415E+00	-.70708E-01	.46403E-02
2	.19014E+00	-.10256E+01	.20574E+00	-.13534E-01
3	-.10157E+01	.54533E+00	-.10912E+00	.71667E-02

ABSORPTION RMS Error = 0.6%

i \ j	0	1	2	3
0	.66103E-01	.34702E-01	-.69662E-02	.44253E-03
1	-.79484E-01	-.73614E-01	.17572E-01	-.10788E-02
2	.29293E+00	.25047E+00	-.55398E-01	.35139E-02
3	-.22077E+00	-.13272E+00	.28740E-01	-.17990E-02

Table 8. Approximating predictor coefficients, b_{ij}, for an altostratus cloud

REFLECTION RMS Error = 1.3%

i \ j	0	1	2	3
0	.64457E+00	.28785E+00	-.12069E+00	.16673E-01
1	.44388E+00	-.45496E+00	.18695E+00	-.26672E-01
2	-.14875E+01	.13141E+01	-.54825E+00	.77121E-01
3	.85585E+00	-.71346E+00	.29823E+00	-.41922E-01

TRANSMISSION RMS Error = 1.5%

i \ j	0	1	2	3
0	.30735E+00	-.35373E+00	.14797E+00	-.20208E-01
1	-.44042E+00	.50188E+00	-.20975E+00	.28630E-01
2	.13537E+01	-.15738E+01	.66248E+00	-.90739E-01
3	-.73396E+00	.85256E+00	-.35858E+00	.49077E-01

ABSORPTION RMS Error = 0.4%

i \ j	0	1	2	3
0	.70594E-01	.40901E-01	-.16982E-01	.21345E-02
1	-.28640E-01	-.18917E-01	.11167E-01	-.37025E-03
2	.19500E+00	.19298E+00	-.86520E-01	.98269E-02
3	-.15133E+00	-.10728E+00	.47143E-01	-.53524E-02

Table 9. Approximating predictor coefficients, b_{ij}, for a stratus cloud

REFLECTION RMS Error = 1.5%

i \ j	0	1	2	3
0	.38094E+00	.26622E+00	-.62460E-01	.49964E-02
1	.88882E+00	-.39997E+00	.95133E-01	-.76756E-02
2	-.26293E+01	.11593E+01	-.28004E+00	.22779E-01
3	.14876E+01	-.64913E+00	.15951E+00	-.13106E-01

TRANSMISSION RMS Error = 1.5%

i \ j	0	1	2	3
0	.57723E+00	-.32665E+00	.76160E-01	-.60763E-02
1	-.88652E+00	.52284E+00	-.12434E+00	.10020E-01
2	.25788E+01	-.15559E+01	.37421E+00	-.30349E-01
3	-.13906E+01	.85278E+00	-.20753E+00	.16969E-01

ABSORPTION RMS Error = 0.6%

i \ j	0	1	2	3
0	.63909E-01	.48691E-01	-.11011E-01	.36647E-03
1	-.25430E-01	-.11109E+00	.26393E-01	-.21154E-02
2	.11770E+00	.36211E+00	-.85429E-01	.68359E-02
3	-.13761E+00	-.18136E+00	.42026E-01	-.33420E-02

Table 10. Approximating predictor coefficients, b_{ij}, for a cirrus cloud

REFLECTION RMS Error = 1.5%

i \ j	0	1	2	3
0	.25264E+00	.45462E+00	-.29492E+00	.82536E-01
1	-.29273E+00	.22029E+01	-.24834E+01	.82674E+00
2	-.24531E+00	-.63610E+01	.75864E+01	-.25896E+01
3	.35097E+00	.38933E+01	-.49188E+01	.17187E+01

TRANSMISSION RMS Error = 1.7%

i \ j	0	1	2	3
0	.78722E+00	-.66348E+00	.44495E+00	-.12500E+00
1	.73255E+00	-.43772E+01	.47094E+01	-.15549E+01
2	-.68508E+00	.11764E+02	-.13716E+02	.46796E+01
3	.15453E+00	-.70865E+01	.87472E+01	-.30566E+01

ABSORPTION RMS Error = 0.1%

i \ j	0	1	2	3
0	.49388E-01	.13715E+00	-.10122E+00	.28402E-01
1	-.19622E+00	.11882E+01	-.12267E+01	.40299E+00
2	.24118E+00	-.23149E+01	.28776E+01	-.10168E+01
3	-.94420E-01	.11305E+01	-.15772E+01	.58577E+00

CHAPTER 4

PARAMETERIZATION OF THE SURFACE REFLECTION

The parameterization of reflection, transmission and abosrption of solar radiation by clouds described in the previous chapter does not include the effect of multiple reflections between the earth's albedo surface and the cloud base. Schneider and Dickinson (1976) emphasized the importance of these multiple reflections in determining the solar flux reaching the surface, especially in climate models which predict snow and ice cover.

To include the surface reflection and the atmospheric effect between the cloud and the earth's surface, the surface is assumed to reflect according to Lambert's law with a surface albedo of A_s. Rayleigh scattering between the cloud and surface is not considered and the absorption between the cloud and surface is assumed to be mainly due to water vapor. The average reflection, transmission and absorption of solar radiation by cloud layers is then defined as follows:

$$\overline{r} = 2 \int_0^1 r(\mu_o)\mu_o \, d\mu_o \tag{17}$$

$$\overline{t} = 2 \int_0^1 t(\mu_o)\mu_o \, d\mu_o \tag{18}$$

$$\overline{\alpha} = 2 \int_0^1 \alpha(\mu_o)\mu_o \, d\mu_o \tag{19}$$

Note that $\bar{r}$ is equivalent to the spherical albedo which represents the reflecting power of the entire planet.

Figure 13 depicts the surface reflection contribution to the upward flux at the cloud base. This additional fraction of the upward flux reaching the cloud bottom may be expressed in terms of an infinite series as follows:

$$
\begin{aligned}
f(\mu_o) &= t(\mu_o)\left[(1-a)^2 A_s + (1-a)^4 A_s^{\,2}\,\bar{r} + (1-a)^6 A_s^{\,3}\,\bar{r}^2 + \ldots\right] \\
&= t(\mu_o)(1-a)^2 A_s\left[1 + (1-a)^2 A_s\,\bar{r} + (1-a)^4 A_s^{\,2}\,\bar{r}^2 + \ldots\right] \\
&= t(\mu_o)\,\frac{(1-a)^2 A_s}{1-(1-a)^2 A_s\bar{r}}
\end{aligned}
\tag{20}
$$

where a represents the water vapor absorption between the cloud base and the earth's surface. Letting the superscript * denote parameters which include the surface effect, the actual cloud reflection, transmission and absorption values are then given by

$$r^*(\mu_o) = r(\mu_o) + f(\mu_o)\,\bar{t}\,, \tag{21}$$

$$t^*(\mu_o) = t(\mu_o) + f(\mu_o)\,\bar{r}\,, \tag{22}$$

$$\alpha^*(\mu_o) = \alpha(\mu_o) + f(\mu_o)\,\bar{\alpha}\,. \tag{23}$$

Equations (21) and (22) are equivalent to those derived by Chandrasekhar (1950) for the reflected and transmitted intensities in the planetary problem based on the principles of invariance.

The water vapor absorption a depends on the water vapor path length and atmospheric pressure. Liou and Sasamori (1975) modified

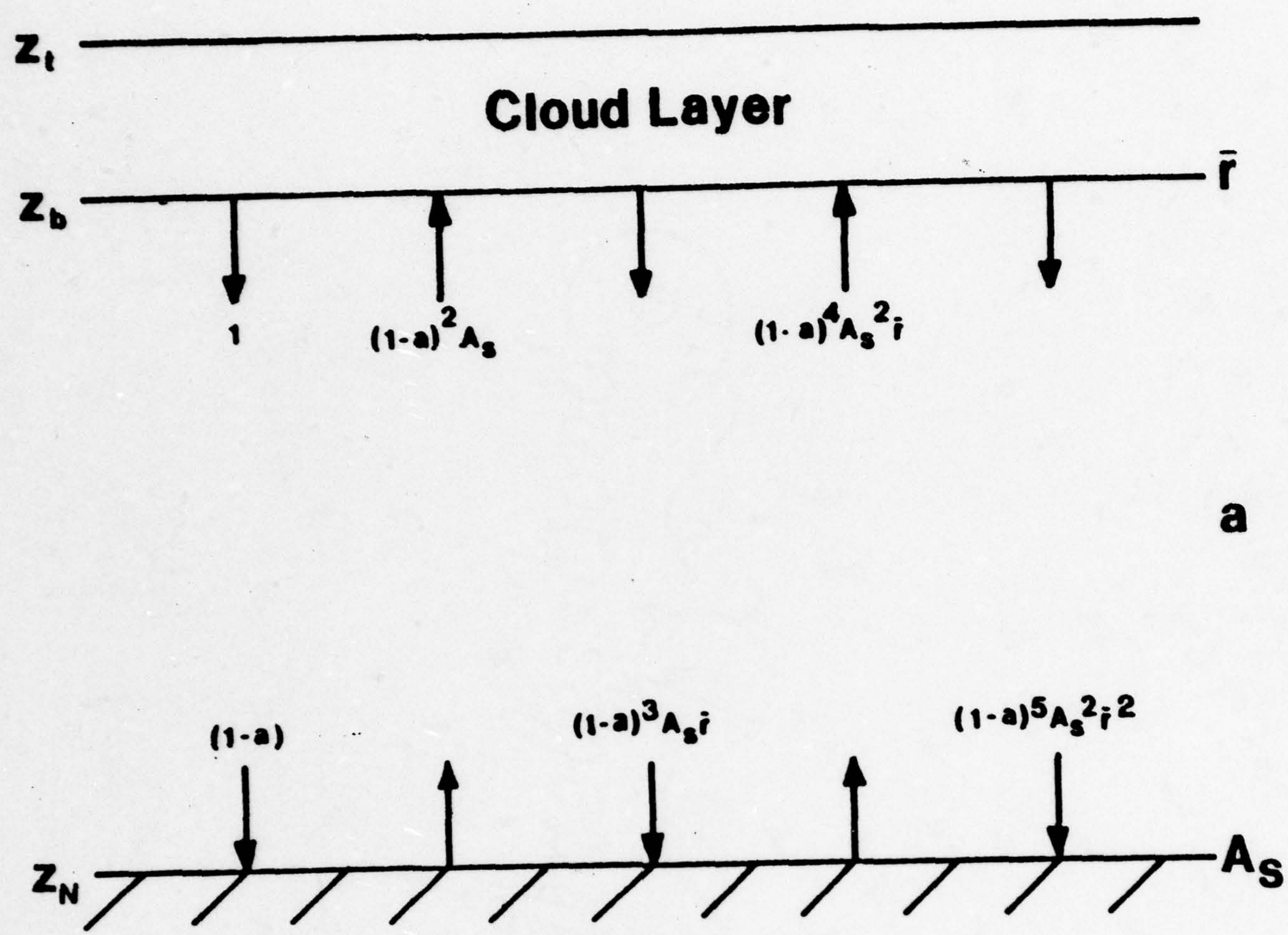

Figure 13. Surface reflection contribution to the upward flux at the cloud base.

the spectral absorptivities of water vapor and carbon dioxide for strong and weak bands based on measurements of Howard et al. (1956) and gave a general expression in the form

$$a_i = \frac{1}{\Delta\nu}\left[C_i + D_i \log_{10}(X_i + X_{oi})\right] , \tag{24}$$

where

$$X_i = uP^{K_i/D_i}$$

$$X_{oi} = 10^{-C_i/D_i} .$$

In the above equations, $\Delta\nu$ is the spectral width of the absorption band, u the water vapor path length, P the atmospheric pressure and C, D and K are constants. Thus, the total water vapor absorption between the cloud and the surface may be obtained by

$$a(u,\overline{P}) = \sum_i a_i(u,\overline{P})\left[f_i/S_o\right] , \tag{25}$$

where the summation is for all the water vapor absorption bands in the solar spectrum and $\overline{P}$ denotes the mean pressure between the cloud and surface.

Equations (21) - (23) were used to compute the reflection, transmission and absorption values for non-zero surface albedos. These values were compared with those calculated from the inhomogeneous transfer program involving the surface reflection. Figure 14 shows this comparison for a cumulus cloud in a tropical atmosphere with a surface albedo of 0.4. Comparisons were made for different cloud types, atmospheres, and surface albedos and revealed that differences between

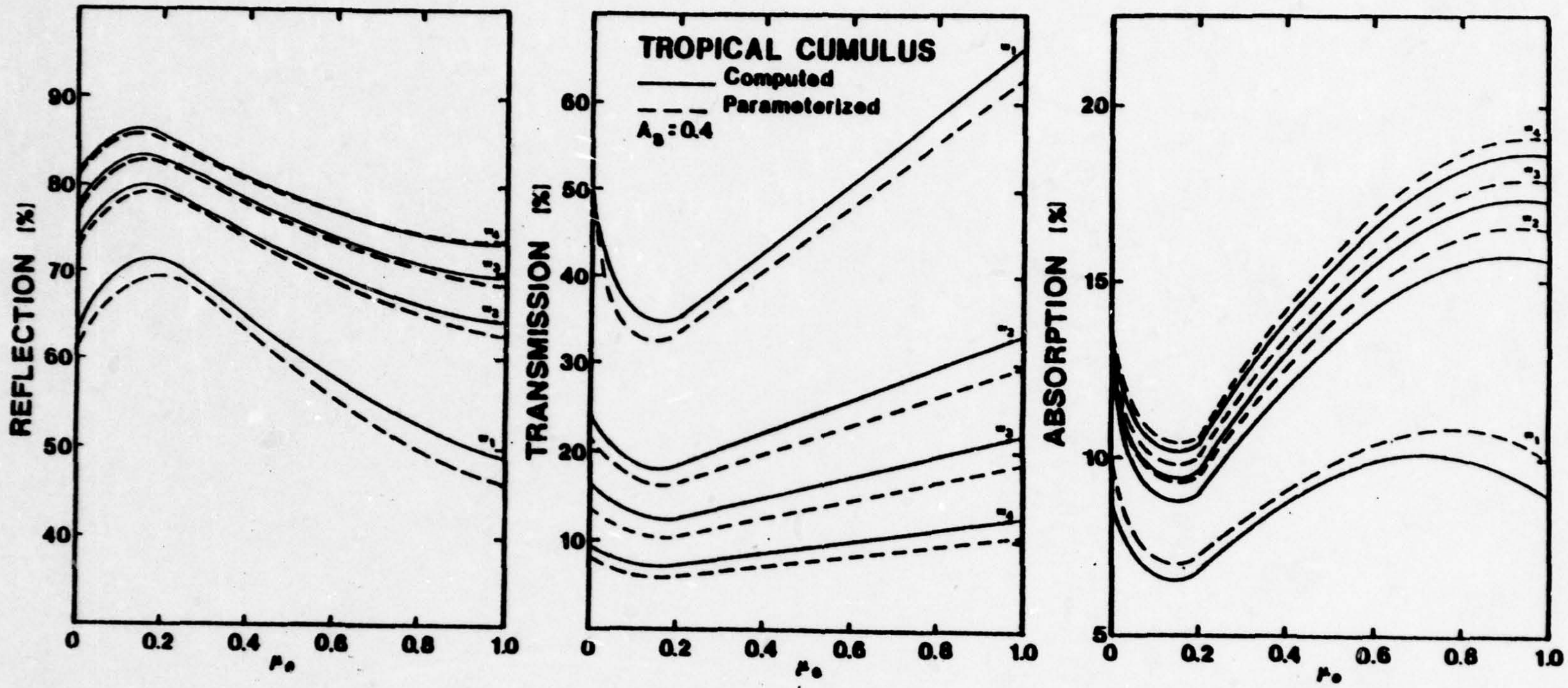

Figure 14. Comparision of solar radiative properties of a cumulus cloud as calculated by the transfer program and the albedo parameterization.

the two methods were generally less than about 2%.

Calculations were also made using the surface reflection parameterization as described previously except that the water vapor absorption between the cloud base and the earth's surface was neglected; i.e. a is zero in Eq. (20). The values for reflection and transmission showed no significant difference from those which considered the absorption by water vapor; however, the error in absorption values was about 2-3% greater.

It was shown in the previous chapter that the error of the parameterization of the solar radiative properties of clouds was less than 2% for each of the four cloud types. In addition, Figure 14 shows that the error of the surface reflection parameterization is also less than 2%. Figure 15 displays the comparison between reflection, transmission and absorption values calculated from the inhomogeneous transfer program and from the combination of the two parameterizations described previously. These values are again for a cumulus cloud in a tropical atmosphere with a surface albedo of 0.4. Comparisons made with the four cloud types showed that the difference of values was normally less than 3%.

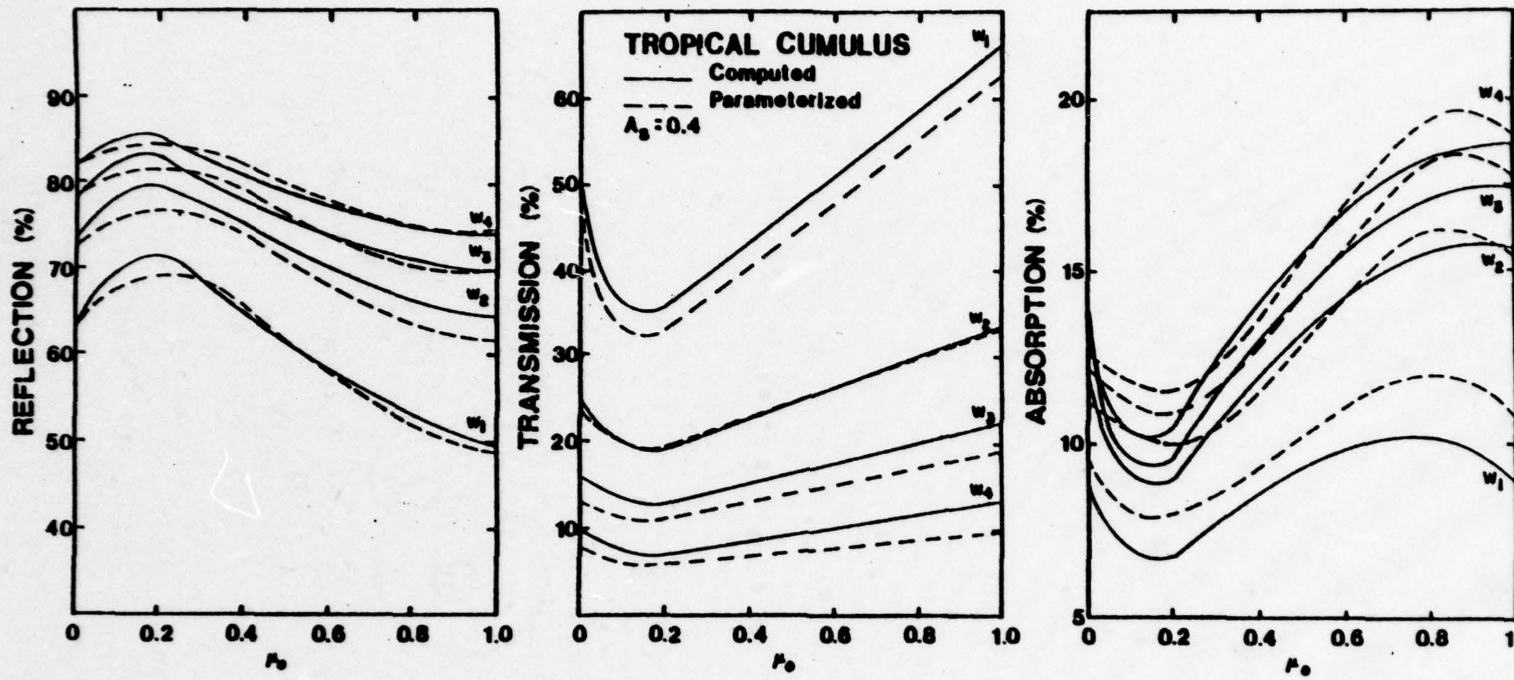

Figure 15. Solar radiative properties of a cumulus cloud in a tropical atmosphere as computed by the transfer program and the parameterized equations.

CHAPTER 5

PARAMETERIZATION OF REFLECTIVITY, TRANSMISSIVITY AND EMISSIVITY OF INFRARED RADIATION BY A CIRRUS CLOUD

Since cirrus clouds may not be considered black bodies as are other cloud types, their infrared radiative properties are quite important in studies of the weather, climate and radiation balance of the earth-atmosphere system. The infrared portion of the radiative transfer model was used to obtain the fluxes necessary to compute the reflectivity, transmissivity and emissivity of infrared radiation by a cirrus cloud. These infrared radiative properties of a cirrus cloud were computed over the range of vertical ice contents listed in Table 6. The flux of radiation emitted by the atmosphere and entering the cloud base, $F^{\uparrow}(\tau_b)$ and the flux of radiation due to atmospheric emission entering the cloud top, $F^{\downarrow}(\tau_t)$, were set equal to zero when calculating the emissivity of the cloud so that the effect of atmospheric emission was not included. On the other hand, the Planck function within the cloud layer was set equal to zero when calculating the reflectivity and transmissivity in order to exclude the effect of the cloud emission.

The plots of the computed radiative properties are displayed in Figure 16. From these plots it can be seen that each of the radiative properties become nearly constant beyond a vertical ice content of 100 g $\cdot$ m^{-2} (approximately 2 km geometrical thickness); therefore, computations beyond 150 g $\cdot$ m^{-2} were not required. There is also a

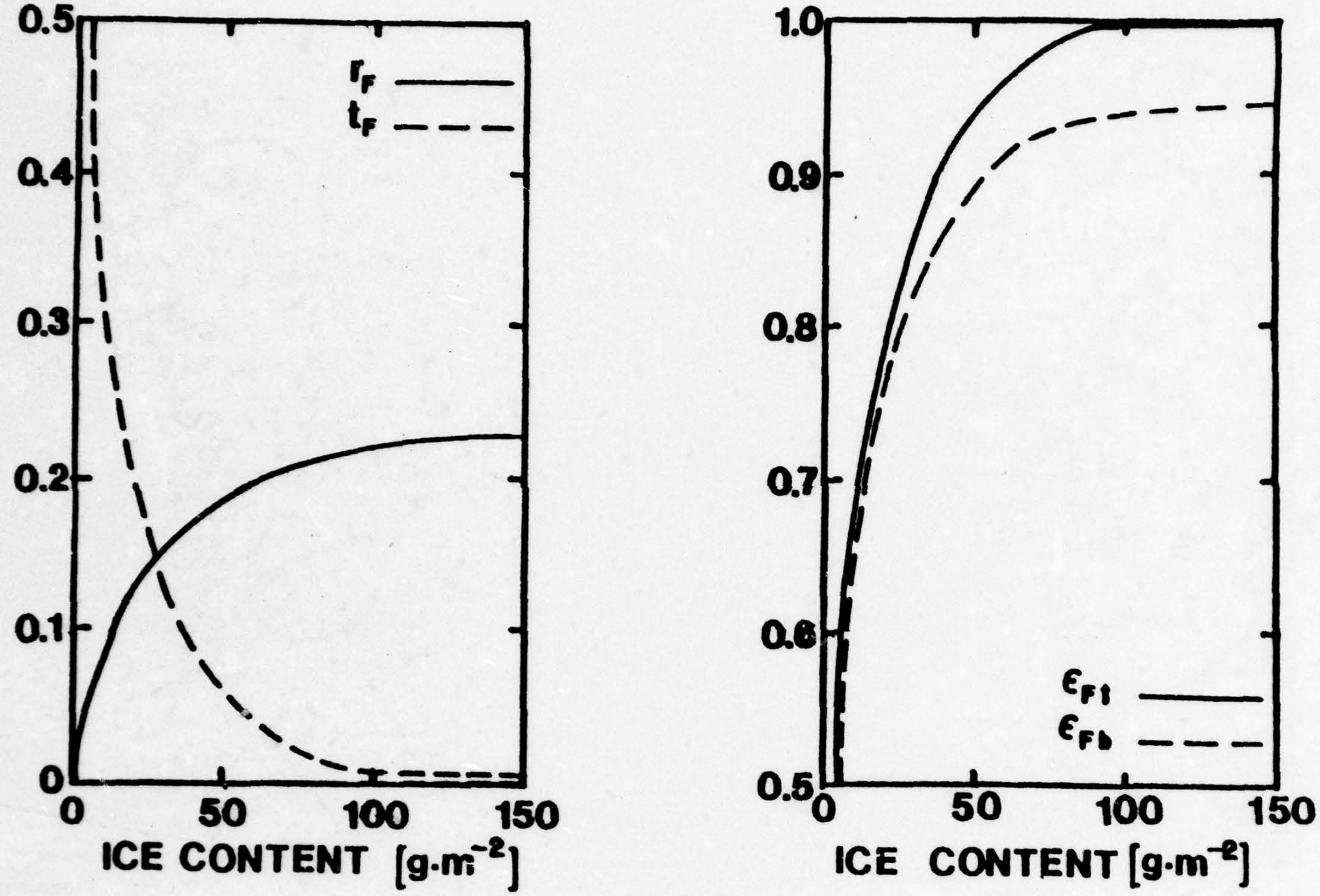

Figure 16. Infrared radiative properties of a cirrus cloud.

significant difference between the emissivities of the cloud at its base and top. This is due to the temperature gradient within the cloud layer ($T_b > T_t$). Since the emission of the cloud is dependent upon its temperature, the emission of the cloud sub-layers below the cloud top will be greater than the emission of the sub-layer at the cloud top. This will cause a positive flux divergence in the upward direction and a negative flux divergence in the downward direction. Consequently, the cloud emissivity is less at the cloud base than at the cloud top.

The reflectivity, transmissivity and emissivity curves were fit to an approximating polynomial equation using a least squares technique similar to that described in Chapter 3. The following polynomial equation provided the best fit of the data:

$$R(W) = \sum_{i=o}^{5} c_i W^i \qquad (26)$$

where R(W) denotes the flux reflectivity, transmissivity or emissivity of the cirrus cloud, c_i the predictor coefficients and W the vertical ice content in units of 10^2 $g \cdot m^{-2}$.

Table 11 lists the coefficients which were computed for the various infrared radiative properties of the cirrus cloud. In each case, the root mean square error of the approximating functions is less than 1%.

Table 11. Approximating predictor coefficients, c_i, for a cirrus cloud

i	Reflectivity	Transmissivity	Emissivity (Cloud Top)	Emissivity (Cloud Base)
0	.30619E-01	.73597E+00	.28363E+00	.28773E+00
1	.81134E+00	-.38162E+01	.36135E+01	.34309E+01
2	-.18995E+01	.83288E+01	-.77273E+01	-.75277E+01
3	.24900E+01	-.91066E+01	.83695E+01	.82498E+01
4	-.15805E+01	.48765E+01	-.44646E+01	-.44163E+01
5	.37581E+00	-.10141E+01	.92724E+00	.91693E+00

CHAPTER 6

THE RADIATION BALANCE OF THE EARTH-ATMOSPHERE SYSTEM

The parameterized equations which were derived for the solar and infrared radiative properties of clouds were used in a relatively simple solar and infrared radiation model in order to determine the various components of the radiation balance of the earth-atmosphere system. The following sections of this chapter include descriptions of the solar and infrared portions of the radiation balance model and the complete radiation balance which was calculated.

6.1 The Global Solar Model

The solar radiation balance of the earth-atmosphere system was calculated using the transfer program for the cloudless portions of the atmosphere and the system of parameterized equations for the cloudy portions of the atmosphere. The major factors considered in the determination of the radiation balance are the atmospheric profile, the geometrical properties of clouds, the fractional cloudiness for each cloud type, the earth's surface albedo, the duration of sunlight, and the zenith angle of the sun.

The radiative transfer program calculations for the cloudless portion of the earth-atmosphere system utilized atmospheric profiles of pressure, temperature, density, water vapor and ozone which were derived by averaging the five sets of atmospheric profiles described in Chapter 2.

The cloud geometrical properties which are of interest are height in the atmosphere, thickness and horizontal extent. Table 12 lists the mean values which were obtained by averaging the cloud height distribution values given by Telegadas and London (1954) and the distributions of fractional cloudiness given by London (1957) for the Northern Hemisphere and by Sasamori et al. (1972) for the Southern Hemisphere. These average values take into account the variations with season and latitude. In addition, the fractional cloudiness values for nimbostratus and cumulonimbus clouds were included in the fractional cloudiness of the altostratus. All three cloud types have relatively large optical depths and therefore the solar radiative properties are quite similar.

Table 12. Mean Cloud Heights and Global Fractional Cloudiness

Cloud Type	Cloud Base (km)	Cloud Thickness (km)	Fractional Cloudiness
Cumulus	1.55	0.71	0.09
Altostratus	2.96	0.80	0.18
Stratus	1.18	0.10	0.12
Cirrus	8.35	1.70	0.14

The surface albedo of the earth is also an important parameter since it determines the amount of transmitted solar radiation reaching the surface which is reflected back into the atmosphere to be absorbed or scattered, or to escape back into space as a component of the earth's global albedo. Surface albedo values for the Northern

Hemisphere were taken from the work of Katayama (1967b), and for the Southern Hemisphere from Sasamori et al. (1972). These values were averaged with respect to latitude and season. The global surface albedo was calculated to be 15%.

The duration of sunlight and the solar zenith angle are also important parameters in determining the radiation balance of the earth-atmosphere system. The zenith angle of the sun is computed from

$$\sin\alpha = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h \tag{27}$$

where α is the altitude of the sun (angular elevation above the horizon), ϕ the latitude of the observer, δ the declination of the sun, and h the hour angle of the sun. The cosine of the solar zenith angle is then given by

$$\mu_o = \cos\theta = \cos(90^o - \alpha) \tag{28}$$

In general, the solar zenith angle varies significantly each hour of the day and sunlight duration varies with season as well as latitude. Table 13 shows the weighting factors which were calculated for the six values of μ_o used in the transfer program. These weighting factors compensate for the variations in solar zenith angle and sunlight duration.

Table 13. Weighting Factors for the Cosine of Solar Zenith Angle

μ_o	0.01	0.2	0.4	0.6	0.8	1.0
Weighting Factor	0.096	0.186	0.217	0.267	0.181	0.053

6.2 The Global Infrared Model

The global infrared radiation budget for the earth-atmosphere system is somewhat easier to model than the solar radiation budget since there is no dependence on surface albedo or zenith angle. Therefore, the factors which must be considered in order to compensate for the seasonal and latitudinal variations are the atmospheric profile, the geometrical properties of clouds, and the fractional cloudiness of each cloud type.

The infrared portion of the global radiation balance was calculated using both the transfer program and the parameterized equations for the infrared radiative properties of a cirrus cloud. From the transfer program, values for the upward fluxes at the atmospheric top and the downwelling radiation at the earth surface were obtained using the averaged atmospheric profile, described in the preceding section, and the averaged values of cloud distribution listed in Table 12. The upward flux at the surface was computed using the surface temperature in the Stefan-Boltzmann law

$$F = \sigma T_s^4 \tag{29}$$

In this equation, F is the total flux of infrared radiation emitted by the earth and σ is the Stefan-Boltzmann constant which has a value of 8.128×10^{-11} cal cm^{-2} min^{-1} $^{o}K^{-4}$.

6.3 The Global Radiation Balance

The annual radiation budget of the earth-atmosphere system is presented in Figure 17. The radiation from the sun on the earth, averaged for the entire year, is represented by 100 units. Using a solar

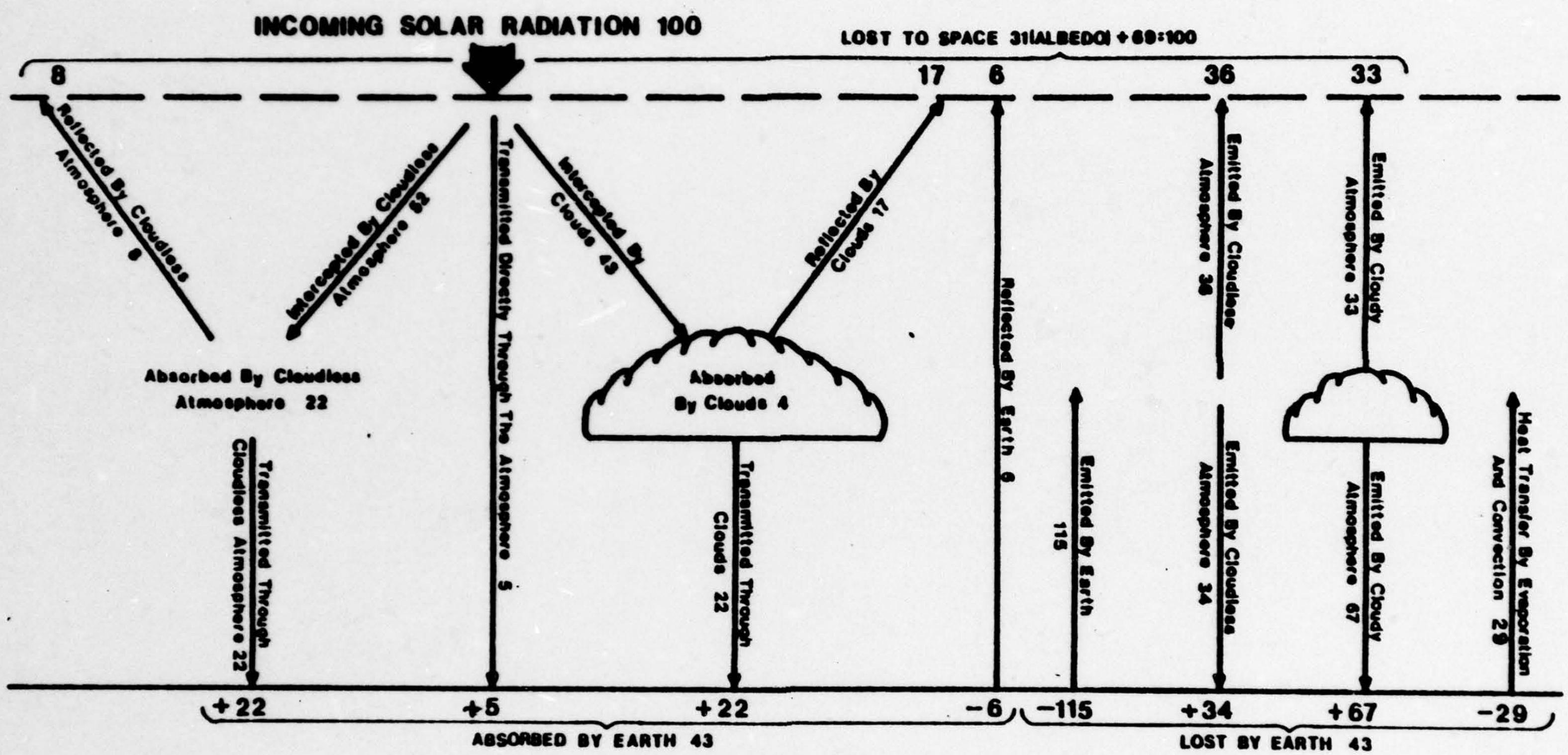

Figure 17. Radiation balance of the earth-atmosphere system.

constant of 1353 $W \cdot m^{-2}$ (Thekaekara, 1976), the average insolation at the top of the atmosphere was calculated to be 0.485 $cal \cdot cm^{-2} \cdot min^{-1}$. Basically, the figure is in three sections, one dealing with solar radiation and the manner in which it is apportioned in the atmosphere; the second concerning infrared radiation and its distribution; and the third dealing with nonradiative processes. For the solar part, the important parameters are the absorption of solar radiation by the cloudless atmosphere and by clouds, absorption and reflection by the earth's atmosphere, and the various components of the reflected radiation at the top of the atmosphere. The parameters of interest for the infrared radiation include the upward flux at the earth's surface, the upward flux at the atmospheric top, and the net loss of infrared radiation from the atmosphere. The net upward flux at the surface is the difference between the flux emitted by the surface and the downward flux from the atmosphere reaching the surface. This is always a positive quantity since the black-body emission from the earth is always greater than the non-black emission from the cooler atmosphere. The net loss from the atmosphere is the difference between the upward flux at the top of the atmosphere and the net upward flux at the surface.

The radiative balance between the surface of the earth and the atmosphere involves fluxes of latent and sensible heat in addition to the radiational fluxes. In this study, no attempt has been made to make an independent estimate of these nonradiative components of the radiation balance. The flux of latent and sensible heat represented in Figure 17 has been selected to produce an overall balance at the surface. Consequently, it includes the integrated errors of the other

components of the global radiation balance. The average annual ratio of sensible to latent heat loss at the surface (Bowen ratio) is approximately 0.22 for the Southern Hemisphere and 0.32 for the Northern Hemisphere (Sasamori et al., 1972). Therefore, the global value of the latent heat component is 23 units and the sensible heat component is 6 units.

In Table 14 comparisons between the present study and previous models are presented for the solar radiation absorbed and reflected by the earth-atmosphere system, the net upwelling infrared radiation at the earth's surface, the total upwelling infrared radiation at the atmospheric top, the net infrared radiation absorbed by the atmosphere, and the latent and sensible heat transport. It should be noted that the works of Houghton (1954) and London (1957) are for the Northern Hemisphere and that of Sasamori et al. (1972) is for the Southern Hemisphere only.

The differences in the absorption and reflection of solar radiation by clouds between the various studies is partially due to the different cloud distributions, but is primarily caused by the parameterization methods used in the models. Houghton used a single set of cloud albedos for the entire model, while London and Sasamori used a range of values dependent upon cloud thickness and to some extent upon the solar zenith angle, but do not include the additional effect of the surface reflection which is included in the parameterization developed in this study.

The total absorption of solar radiation computed in the present work exceeds the absorption computed by the previous investigators.

Table 14. Annual Radiation Budget of the Earth-Atmosphere System

	Houghton(1954)	London(1957)	Sasamori(1972)	Present Study
I. SOLAR RADIATION				
1. Insolation at top of atmosphere	100	100.0	100	100
2. Absorption in the atmosphere				
a. by the cloudless atmosphere	9	15.8	17	22
b. by clouds	10	1.6	4	4
Total Absorption	19	17.4	21	26
3. Reflection and scattering back to space				
a. by atmosphere	9	6.8	6	8
b. by clouds	25	24.2	29	17
c. by earth's surface	---	4.2	---	6
Total Reflection	34	35.2	35	31
4. Absorbed by earth's surface				
a. direct	24	22.4	24	5*
b. transmitted through clouds	17	14.4	---	22*
c. scattered	6	10.6	21	22*
Total Absorption at Earth's Surface	47	47.4	45	43
II. INFRARED RADIATION				
1. Net radiation from earth's surface				
a. total emission by earth	119	114.4	112	115
b. back radiation from cloudless atmosphere	---	---	---	34
c. back radiation from cloudy atmosphere	---	---	---	67
d. total back radiation	105	96.4	96	101
Net Radiation from Earth's Surface	14	18.0	16	14

Table 14. (Continued)

	Houghton(1954)	London(1957)	Sasamori(1972)	Present Study
2. Infrared radiation lost to space				
a. from cloudless atmosphere	---	---	---	36
b. from cloudy atmosphere	---	---	---	33
Total Lost to Space	66	64.8	66	69
3. Net radiation lost by atmosphere	52	46.8	51	55
III. TRANSPORT TO ATMOSPHERE				
1. Latent heat	23	18.6	23	23
2. Sensible heat	10	10.8	7	6
Total Heat Transport	33	29.4	30	29

* These values represent the radiation incident on the earth's surface; therefore, the radiation reflected by the earth's surface has been subtracted from the total.

This is due to the increased absorption from aerosols and the effects of scattering by aerosols and clouds, which increase the amount of energy available for absorption by increasing the optical path length through the atmosphere.

The comparisons of planetary albedo show that the present calculations yield an albedo which is 3-4% lower than those of the older works; however, the planetary albedo value, 0.31, of this work is in good agreement with those derived from satellite observations. Vonder Haar and Suomi (1971) calculated an albedo of 0.30 from TIROS, Nimbus and ESSA satellite measurements for the period 1962-1966. Raschke and Bandeen (1970) measured an albedo of 0.29 to 0.31 for June and July of 1966 from Nimbus 2 satellite observations. Raschke et al. (1973), using Nimbus 3 measurements from 1969-1970, evaluated the global albedo at 0.284. More recently, Smith et al. (1977), using Nimbus 6 earth radiation budget experiment data, computed the global albedo to be 0.30. The difference of the planetary albedo derived by this model and the satellite observed values are probably due to the overestimation of cloudiness and the underestimation of absorption in the atmosphere due to the uncertainties and inaccuracies in the treatment of aerosols.

The infrared radiation emitted from the earth's surface and the atmosphere, as computed by the model used in this study, are somewhat greater than those calculated previously. Consequently, the net radiation from the earth's surface is smaller and the net radiation lost by the atmosphere is greater than those of the earlier works. These differences result mainly from the different water vapor, ozone, temperature and cloud distributions used. The parameterization of the

radiative properties of the non-black cirrus cloud also plays a significant role in the overall emission of the earth-atmosphere system. The present study is, however, in good agreement with the satellite observed upwelling infrared flux. The studies of Smith et al. (1977) and Vonder Haar and Suomi (1971) calculated values which equal 70% of the incoming solar radiation.

CHAPTER 7

CONCLUSIONS

Clouds are the most important atmospheric elements involved in the complex interactions of the radiation field. In this study, the cloud effects were carefully reproduced by the comprehensive radiative transfer program and then parameterized into simplifying empirical-theoretical equations for both the solar and infrared radiative properties of clouds. The reflection, transmission and absorption of solar radiation by four cloud types are parameterized by polynomial equations in terms of the solar zenith angle and the cloud vertical liquid water/ice content. Parameterized equations for the infrared reflectivity, transmissivity and emissivity of cirrus clouds are expressed in terms of the cloud vertical ice content.

By employing various different atmospheric profiles, the effect of the atmospheric profile on these radiative properties of clouds is shown to be insignificant. However, the cloud type, which is represented by a distinct particle size distribution, does have a significant influence on the values. The additional effect of the surface reflection upon the reflection, transmission and absorption of solar radiation by clouds is further parameterized in which water vapor absorption between the cloud and the earth's surface is taken into account.

The comprehensive radiative transfer program is also utilized in a

a relatively simple radiation budget model. The global results obtained are in good agreement with earlier radiation budget studies and agree more closely with recent satellite observations than do the earlier works.

Overall, it is felt that the parameterized equations for the solar and infrared radiative properties of clouds proved accurate in the radiation budget model and would be useful and practicable in connection with the study of the climate and climatic changes of the earth-atmosphere system.

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